Use of Climate Model Data for Assessing the Effects of Climate Change on Water Resources: Uncertainties and Bias Correction

Part 1: Climate Change and Projection of Future Climate

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Organization

Sections 1 & 2 for the 1st lecture, Section 3 for the 2nd lecture and Section 4 for lab sessions

1. **Recent trends in global temperatures: Origin and consequences?**
   - Attribution of the increasing trend in the global-mean temperatures in the recent century
   - Regional impacts

2. **Uncertainties in projecting future water resources due to climate model data**
   - Uncertainties in GCM projections
   - Uncertainties in RCM projections
   - RCM biases over the Africa region in the CORDEX-Africa hindcast experiment

3. **Uncertainties in the climate forcing data for driving surface hydrology models**
   - Transferring the gridded climate model data to irregularly shaped watershed areas
   - Climate model biases and bias correction

4. **Lab demo:** *Application of the Regional Climate Model Evaluation System* (*RCMES*) for climate model data evaluation and bias correction
   - The Sacramento River basin in northern California as an example.
   - Regional climate model hindcast data from the North American Regional Climate Change and Assessment Project (NARCCAP).
   - Processing of data from multiple RCMs to construct forcing time series for bulk hydrology models
   - Examination of the biases in the forcing time series – individual models and model ensemble
   - Bias correction – Annual cycle matching (daily & monthly), quantile mapping

Why do we concern climate model biases in projecting future water resources?

- Water resources are directly related with regional water and energy cycle.
    - Precipitation, Evapotranspiration, Runoff, Groundwater aquifer, Soil moisture content

- Regional water and energy cycle is affected by global circulation.
- Water vapor transport (storm tracks), Insolation, Air temperature, Winds

- Thus, projecting future climate under conceivable external forcings is the key in projecting future water resources.

- Thus, uncertainties in future climate climate projections are a major source of uncertainties in projecting future climate.

- In Sections 1 and 2, we will briefly review the uncertainties in projecting future climate state using climate models.

Section 1. Recent trends in global temperatures: Origin and consequences?

1. Global-mean surface temperature trends for the latest 1000 years
   - Historical records show a trend of increasing global-mean surface air temperature in the past century (*Figure 1.1*).
   - The recent warming is a clear and sudden departure from the temperature trend in the latest millennia: *a slight cooling trend of global temperature for the past 1000 years was reversed into a well-defined warming trend during early 20th century and continues*.

2. Attributions of the warming trend - observations
   – The concentration of trace gases that are closely related with industrial activities increases from its pre-industrial values from 1800 (blue arrow in *Figure 1.2*).
   – For all trace gases shown as examples, the rate of increase becomes steeper after 1990 (red arrow in *Figure 1.2*).
   – Theory of radiative transfer and its relationship with surface air temperature suggests that the increased concentration of anthropogenic GHGs and the warming trend may be related.

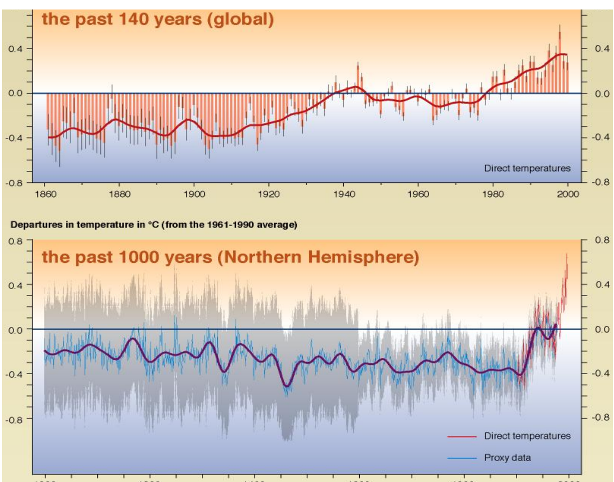


Figure 1.1. The global-mean surface air temperature trend during the latest 1000 years (IPCC AR3, 1991).

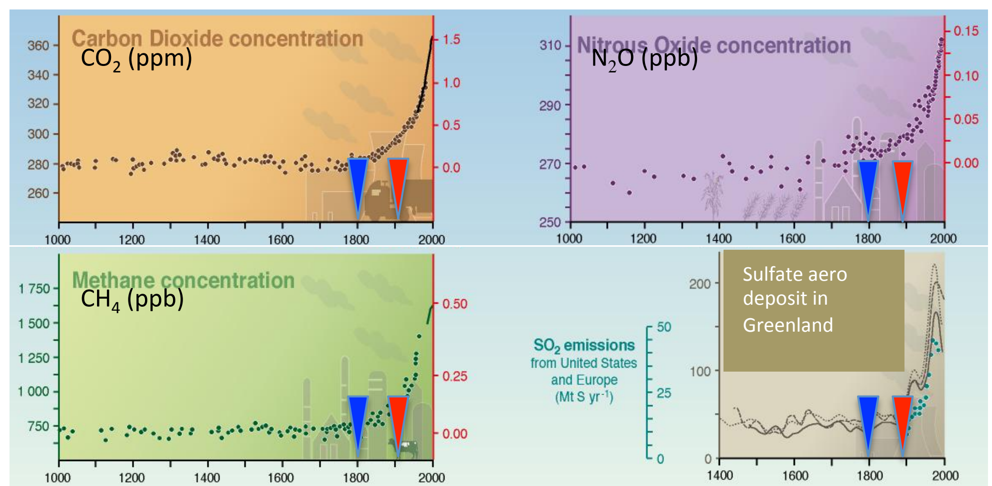


Figure 1.2. Indicators of the human influence on the atmosphere in the industrial era (IPCC AR3, 1991).

Section 1 (continued). Recent trends in global temperatures: Origin and consequences?

- Attributions of the warming trend – climate modeling studies
  - The hypothesis that ***the emissions of anthropogenic GHGs since the industrial age is related with the recent warming trend*** was examined in a number of global climate modeling studies.
  - These experiments typically compare the temperature trends in three GCM runs with – natural forcing only, anthropogenic forcing only, and the combined natural and anthropogenic forcing.
  - It has been concluded that the observed global-mean temperature (black line) trend in the 20th century can be explained best with *the combined natural and anthropogenic forcing* as summarized in IPCC AR4 (*Fig. 1.3*).

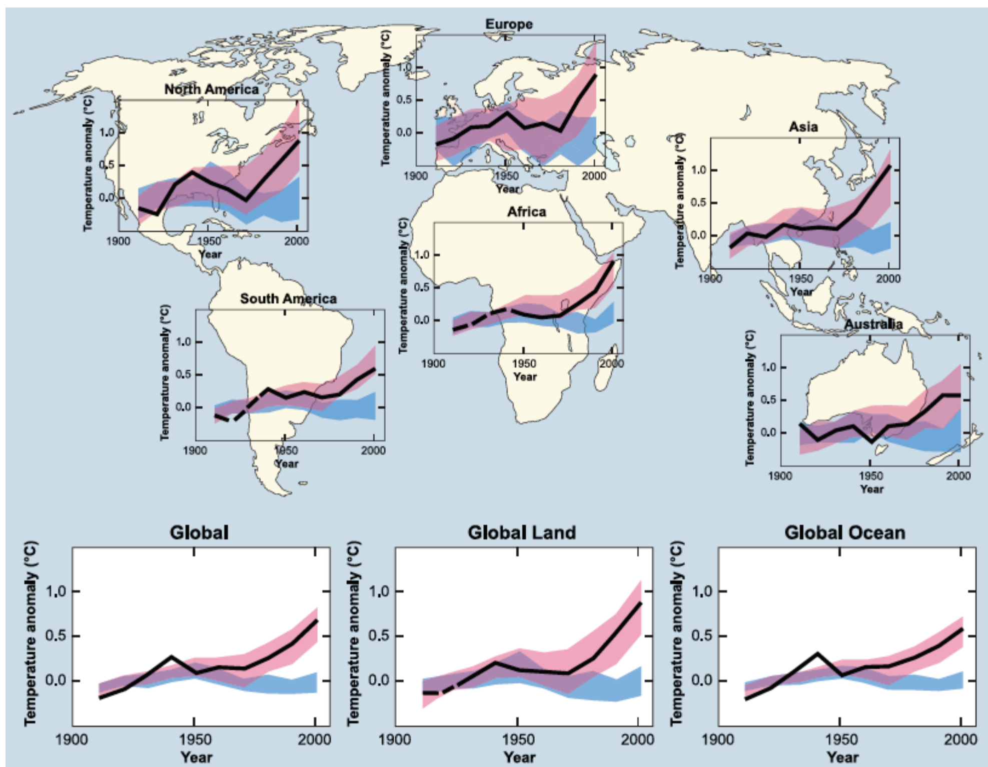


Figure 1.3. Global and continental Temperature Change (*IPCC AR4 Synthesis Report, 2007*); Black – Observation; Blue – natural forcing only ensemble; Red – natural + anthropogenic forcing ensemble.

Section 1 (continued): Regional Impacts from observations

1. Regional variations in the observed temperature trend (*Fig. 1.4*)
   - The observed temperature trends vary widely according to regions.
   - Positive temperature trend occurs over almost the entire globe except in some southern oceans and isolated land points for the period 1976-2000.
   - The observed warming trends are generally larger in higher latitudes than lower latitudes, especially over the northern hemisphere high latitude regions where the impact of warming affects snow/ice cover.

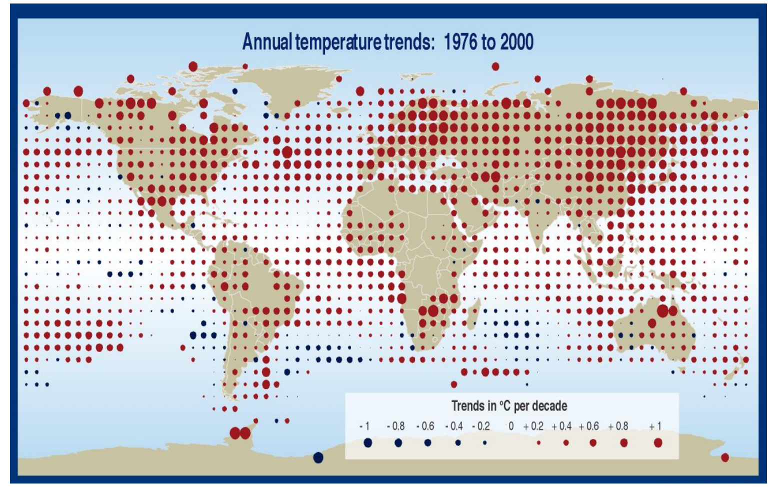


Figure 1.4. The observed regional trends in the annual-mean surface temperature (K/decade) for 1976-2000 (IPCC AR3, 1991).

2. Regional variations in the observed precipitation trend (*Fig. 1.5*)
   – The observed precipitation trend also varies widely according to regions – much larger spatial variations than for the surface temp.
   – Unlike temperature trends, both positive and negative trends over over large areas.
   – The most noticeable drying trend has occurred in the western Sahara, Sahel, Ethiopian Highlands, southern Tibet/northern Indochina, Pacific coast of South America, southwestern US, central Europe and the mid-latitude central Russia.

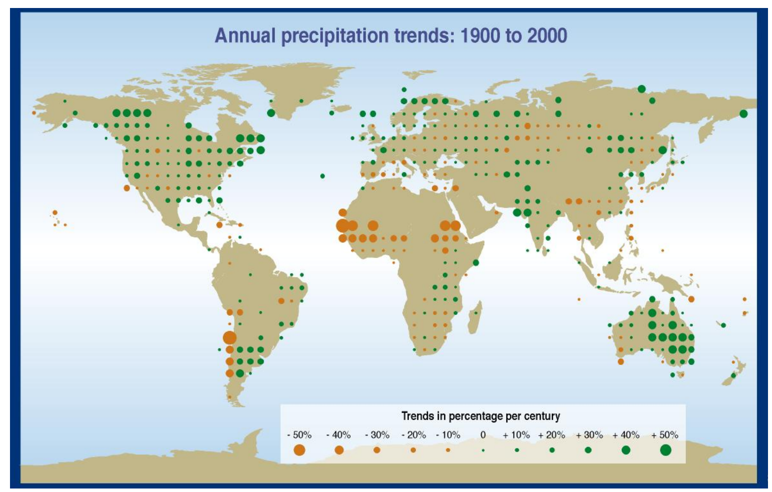


Figure 1.5. The observed regional trends in the annual-mean precipitation (%/century) for 1976-2000 (IPCC AR3, 1991).

3. The large regional variations in the temperature and precipitation trends over the globe (*Figures 1.4* and *1.5*) show that different regions will have to face different effects of the global climate variations and change.
   – Projecting regional climate change is crucial for adapting to and mitigating the effects of global climate change.

Section 2. Uncertainties in projecting future water resources due to climate model data

- Regional climate plays a crucial role in shaping human sectors
  - Regional human societies and industry have evolved according to their natural environments.
  - Human society can adapt to climate changes, but it takes time and resources.

- Projecting the impacts of climate change on regional water cycle is an important concern for all communities worldwide, in particular for *those regions that are susceptible to changes in the surface temperature and precipitation*.
  - Water cycle affects human society; water resources, agriculture, energy, transportation, natural disasters.
  - Water resources are already stretched in arid/semi-arid regions – slight reduction in prec can be disastrous.
  - Regions that rely heavily on mountain snowpack will especially suffer from reduced snowpack accumulation.
  - Regions of steep terrain are vulnerable to floods induced by locally heavy precipitation.

- Thus, assessing the impact of climate change on water cycle and related sectors such as water resources is an important concern for many communities around the world.

- Impact assessments require a hierarchy of nested models, from GCMs for generating global climate scenarios to individual assessment models for translating the changes in climate variables into the changes in water resources (e.g., *Fig. 1.6*).

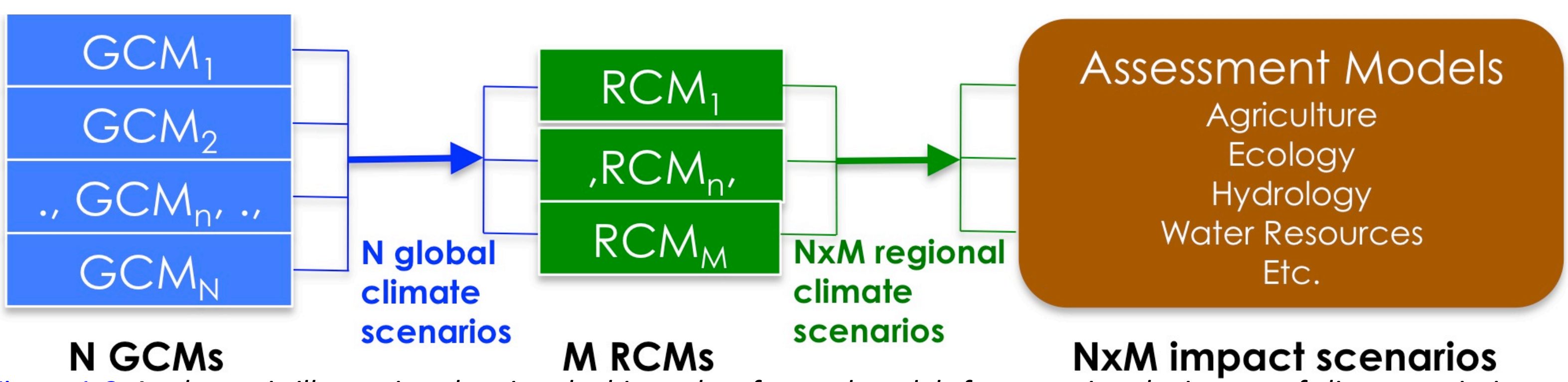


Figure 1.6. A schematic illustration showing the hierarchy of nested models for assessing the impact of climate variations and change on regional sectors (Kim et al. 2013, J of Climate, in press).

Section 2 (continued). Uncertainties due to climate model data

- Human sectors are also a part of Earth's climate system (*Figure 1.7*)
  - Earth's climate responds to the changes in climate system due to human activities, mainly in the GHG concentration, aerosols and land use, by altering the energy and water cycles.
  - Human sectors alter their industrial practices to adjust to the altered climate state (adaptation).
  - The altered human activities in turn affect Earth's climate by the changes in emissions and land use.

- Projection of future climate is challenging especially because, in addition to natural processes, human behaviors that affect climate must be factored in the projection.

- Projections of future climate inevitably includes uncertainties due to *uncertain human interaction with climate* as well as with *model's own incompleteness* in representing the various processes within the climate system.

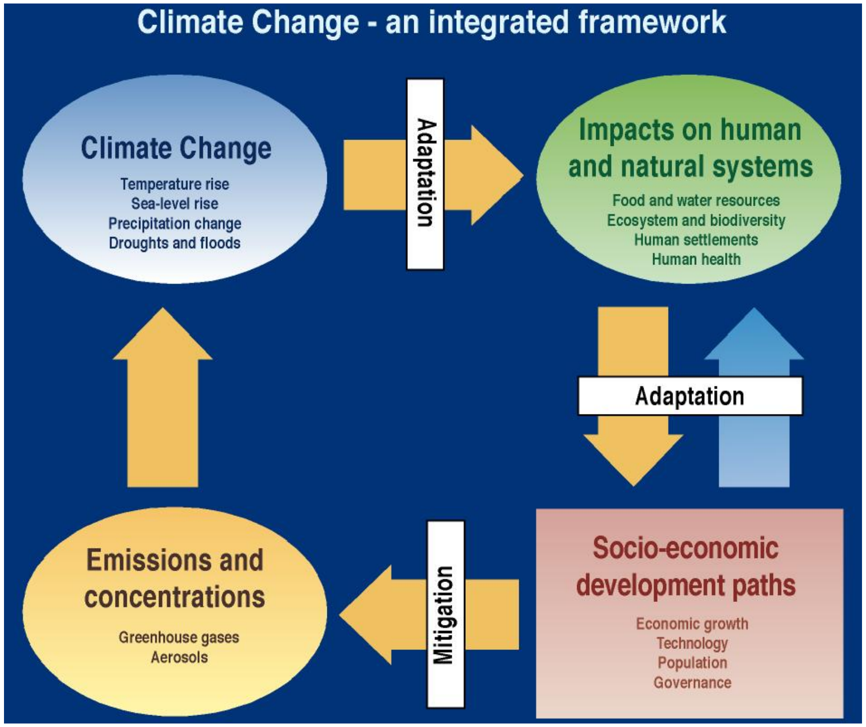


Figure 1.7. A schematic illustration showing the interaction between Earth's climate system and human activities (IPCC AR3, 1991).

Section 2 (continued). Uncertainties due to future human activities

- Among the most serious uncertainties in projecting future climate state is *future emissions* which is the external forcing that alters energy cycle in the climate system via radiative transfer.

- It is difficult to pinpoint future emissions; future emissions depend on a number of factors that are highly interactive and hard to quantify – *it is impossible to exactly determine future GHG emissions profiles*.

- IPCC developed multiple estimates of greenhouse gas emissions scenarios to guide projections of future climate using AOGCMs (*Figure 1.8a*).

- The global mean temperature changes projected by IPCC AOGCM ensembles ranges from 1.8K to 3.8K according to emissions scenarios implemented in GCM runs (*Figure 1.8b*).

- Uncertainties related with future human activities are difficult to deal with; the only way to deal with this type of uncertainty may be to *perform multiple sensitivity study based on multiple emissions scenarios and estimate the range of uncertainties*.

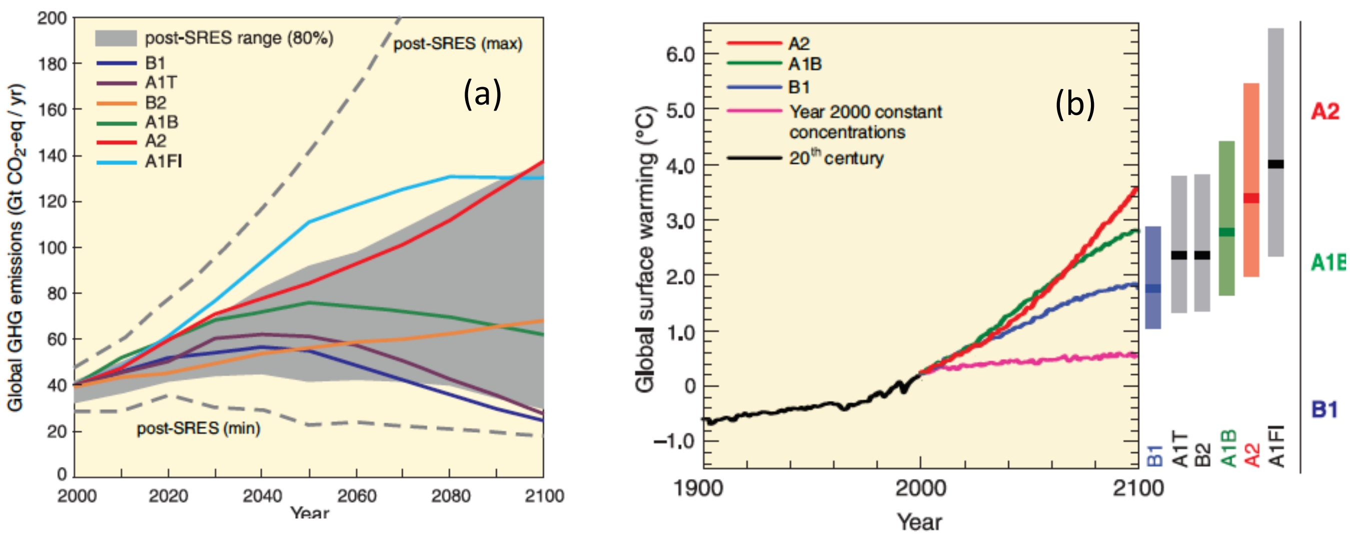


Figure 1.8. (a) SRES GHG emissions scenario for 2000-2100 and (b) Ensemble AOGCM projections of global-mean surface air temperatures corresponding to the various SRES emissions scenarios (IPCC AR4, 2007).

Section 2 (continued). Uncertainties due to climate model formulations

- In addition to the uncertainty in future emissions profiles, climate model errors are also an important source of uncertainties in projecting future climate states.

- The range of projected temperature increases by various AOGCMS for the 3 SRES emissions scenarios range from 2°C for the A2 and B1 scenarios, to 2.5°C for the A1B scenario (*Figure 1.9*).
  – The range of uncertainties among different AOGCMs is comparable to that due to the differences in emissions scenarios.

- Similarly, the variation in the projected precipitation change among AOGCMs is comparable to that due to the differences in emissions scenarios (*Figure 1.9*).
  - Unlike the uncertainties due to emissions scenarios, the uncertainties among AOGCMS originate from the formulations for representing dynamical and physical processes within the individual models.
  - This type of uncertainties can be reduced by improving model formulations.
  - Quantification of model biases may allow us to devise bias correction schemes to alleviate the effects of climate model biases on the subsequent impact assessment models.

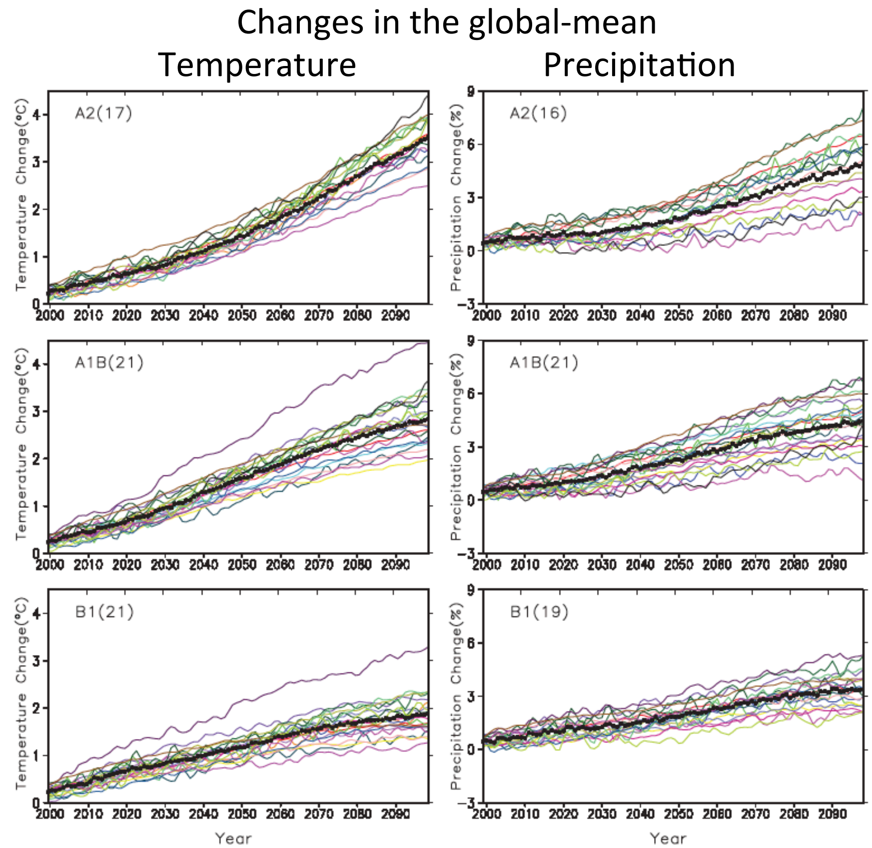


Figure 1.9. Time series of global-mean changes in surface temperature (°C) and precipitation (%) from multiple coupled AOGCMs for the scenarios A2 (top), A1B (middle) and B1 (bottom). Values are annual means, relative to the 20-yr (1980-1999) average from the corresponding 20th-century simulations, with any linear trends in the corresponding control runs removed. Multi-model (ensemble) mean series are marked with black dots.

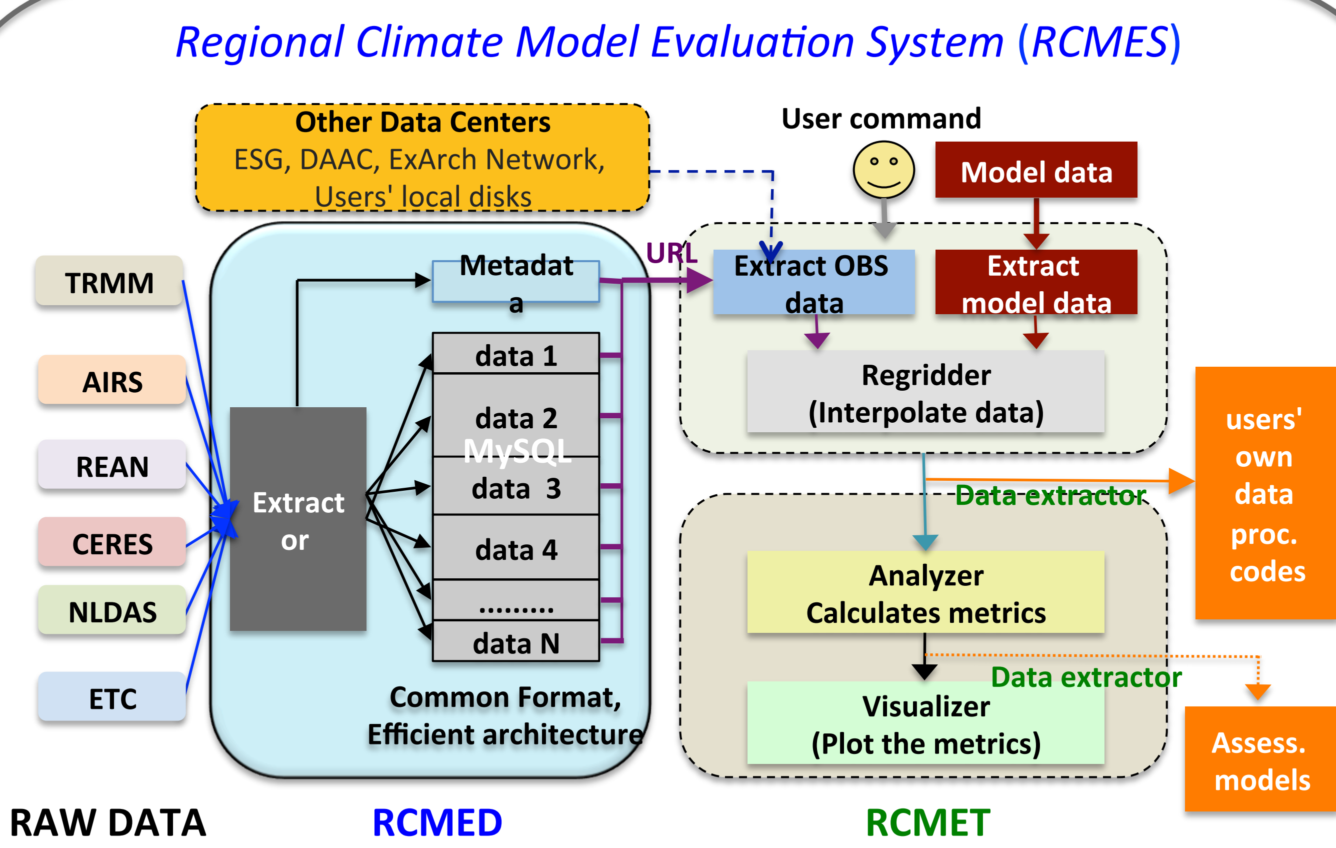


Figure 1.10. A schematic illustration of RCMES.

- Model errors are an important concern in climate change impact assessments.
  - Quantifiable, ideally, in controlled experiments.

- Model evaluation plays an important role in assessing the impact of climate change on regional sectors, especially for bias correction and multi-model ensemble.

- *Regional Climate Model Evaluation System* (RCMES) facilitates access to observational data via open database and toolkit – allows more efforts on research/application and less on data search (*Fig 1.10*).

Section 2 (continued). Evaluation of regional climate models 1

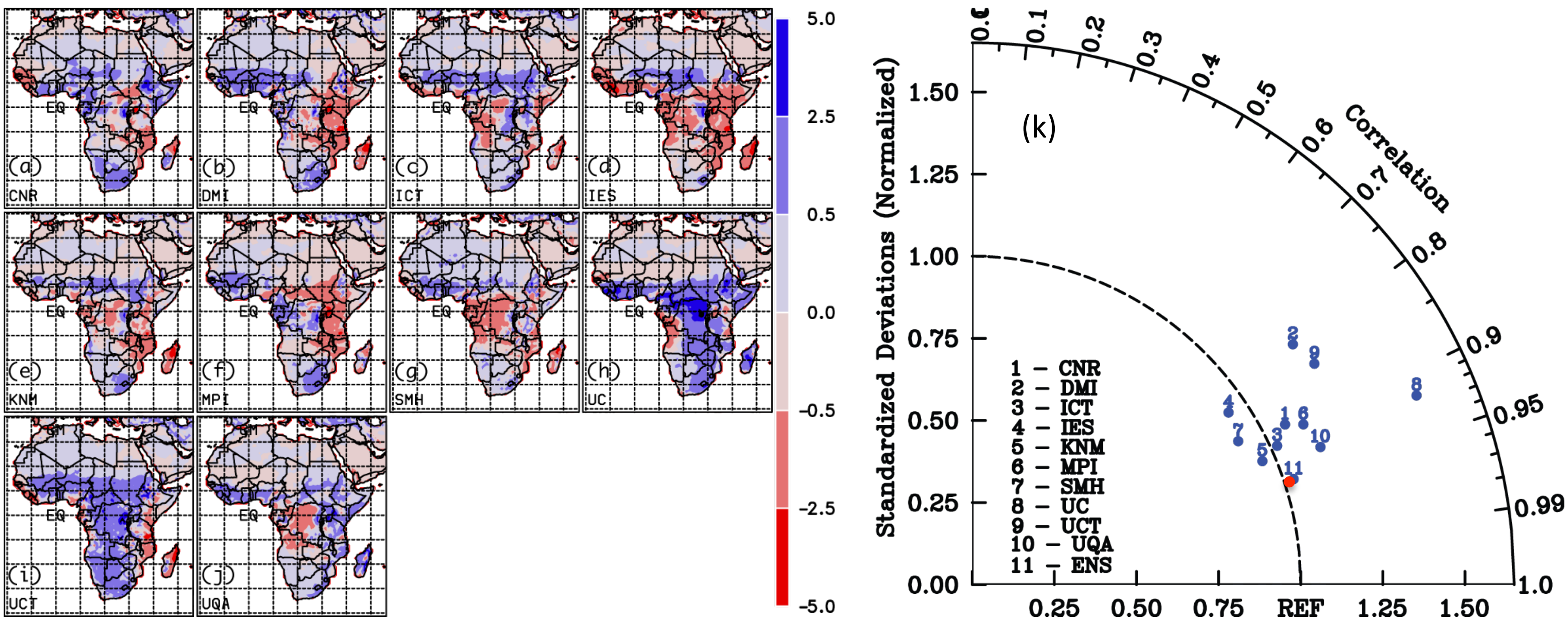


Figure 1.11. Model biases in simulated precipitation climatology over the CORDEX-Africa region for 9 RCMs (a-j). The Taylor diagram (k) evaluates the spatial variability of the simulated climatology in terms of standard deviation and correlation coefficients between the observed and simulated climatology. The red circle indicates the simple multi-model ensemble.

- Model performance in the CORDEX-Africa hindcast experiment is evaluated using RCMES (*Figure 1.11*).
- Model biases (a-j) vary among models – expected from diverse model formulations.
- There also exists regional structure for which all or the majority of models show common bias:
  - All RCMs except (d) generates wet bias in the northwestern Sahara, Sahel and South Africa regions.
  - Most RCMs underestimate annual precipitation in the mid-latitude eastern Africa and the Madagascar island.
- Most models overestimate the magnitude of spatial variability (k).
- The multi-model ensemble (red circle in (k)) yields smaller RMSE than any other models included in the ensemble.

Section 2 (continued). Evaluation of regional climate models 2

- Evaluation of the simulated interannual variability of wet-season rainfall (*Figure 1.12*) shows regionally-systematic variations in model performance.
  - All RCMs show higher fidelity in simulating the phase of the interannual variations, measured in terms of correlation coefficients between the simulated and observed time series, of wet season precipitation for the Sahel region than the Ethiopian highland region.
  - Models tend to underestimate (overestimate) the temporal standard deviation, a measure of the magnitude of interannual variability, for the Ethiopian Highlands than the Sahel region.
  - Like for the spatial variations in the annual climatology (*Figure* 10), the multi-model ensemble performs best for both regions.

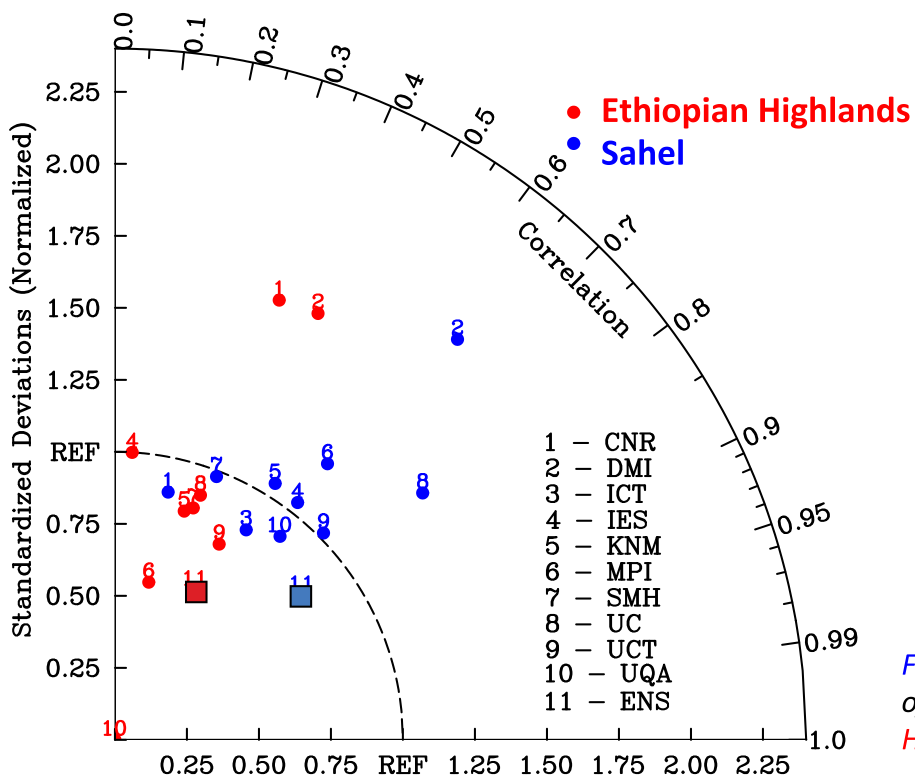
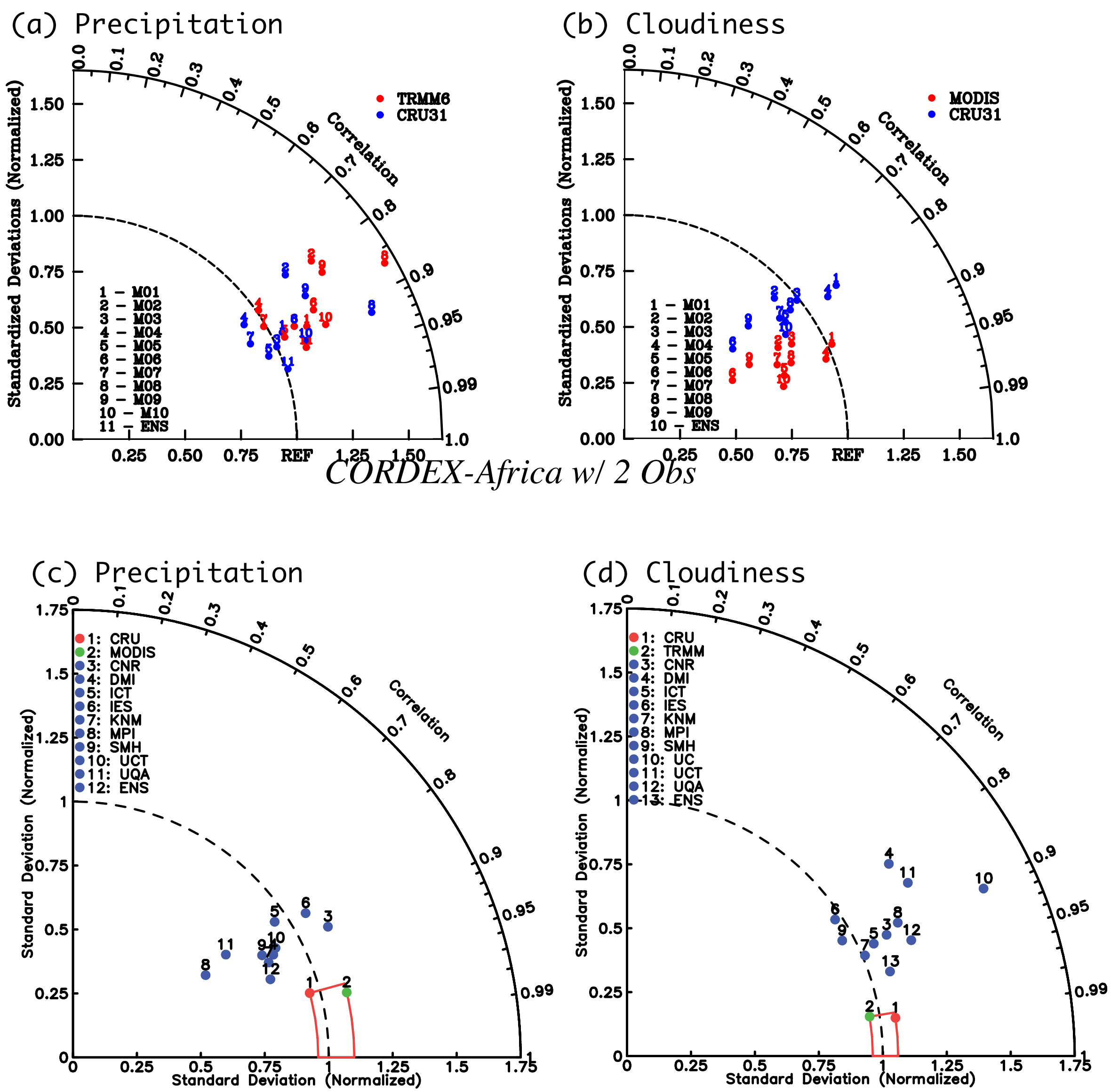


Figure 1.12. Evaluation of the simulated interannual variability of the wet-season rainfall in the Sahel (blue) and Ethiopian Highlands (red).

Uncertainties due to Reference Data



- Reference data can also be a source of uncertainties in model evaluation.
- Individual reference data as well as models are 'evaluated' against the multi-observation ensemble.
- The evaluation metrics of multiple observation datasets vary although they are much smaller than those of models.
- Measured model skills can vary according to the selection of reference data.
- ***Cross-examination of reference data is important***.

Summary of Sections 1 and 2

- Intense research during the recent several decades confirmed with a high level of confidence that *the increase in the surface air temperature, most notably from mid-20th century, is caused by the combinations of natural forcing and the anthropogenic forcing due to the emissions of GHG gases since the industrial revolution*.

- The effects of global climate variations and change on the surface temperature and precipitation vary widely according to regions.

- Human society is strongly influenced by the regional climate characteristics; typically, regional industry and society has been evolved to fit best with their regional climate.

- To adapt to and mitigate the impact of climate change on regional sectors need future climate information.

- Projecting future climate inevitably includes uncertainties due to
- *Interaction between industrial activities and climate system*
- *Incompleteness of the formulations used in climate models* to calculate various processes in the climate sys.

- In typical nested modeling method used for impact assessment, uncertainties propagate through model hierarchy. *Thus quantifying and reducing uncertainties in climate models is an important part of impact assessment studies*.

- The uncertainty related with future industrial activities is very difficult to estimate. This uncertainties is very difficult to handle; IPCC introduced multiple future emissions scenarios as a guide for AOGCM experiments.

- The uncertainty related with climate model formulations may be dealt with via bias correction, multi-model ensemble or both based on rigorous model evaluation.
- Ideally, the biases due to model formulations can be quantified in controlled experiments.

- Evaluation of multi-RCM hindcast in the CORDEX-Africa project reveals that
- *Model biases vary systematically according to regions*
- *Multi-model ensemble performs better than individual models in simulating spatial & interannual variations*.

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